THREE-DIMENSIONAL DEPOSITIONAL SYSTEMS: SOLUTIONS OF THE CONTROLLING DIFFERENTIAL EQUATION

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LONG TERM GOALS

Our long-term goal is to determine how along-shelf versus cross-shelf sediment transport, deposition, and erosion are affected by variations in sediment supply, climate, and relative sea level fluctuations. Toward this goal, we have developed a process-oriented three-dimensional (3D) stratigraphic model to assess how cross-shelf versus along-shelf sediment transport affects the stratal architecture and associated facies developed on continental margins. By simulating the stratal architecture, stacking patterns and associated facies preserved on a number of continental margins (e.g., New Jersey and the Eel river margins), we will be able to examine how relative sea level changes, variations in sediment supply, physiography, and climate affect stratal architecture and facies distribution through time.

SCIENTIFIC OBJECTIVES

The objective of our FY97 project was to redefine the partial differential equation describing both the advective and diffusive transport of sediment to: 1) include a range of various initial bathymetric conditions (e.g., shelf break in addition to ramps), 2) include the effect of gravity and currents in controlling sediment plumes and deposition, and 3) continue to model the stratal architecture preserved on continental margins using our newly defined sediment transport equations. We will focus on the solutions of the sediment transport equation in this report.

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APPROACH

We addressed this problem by recognizing that the original study of Kenyon and Turcotte (1985) was very specific on the boundary and initial conditions used to solve the diffusion differential equation in modeling the spatial and temporal development of progradational systems. In particular, Kenyon and Turcotte (1985) assumed that the sediment prograded into a region of constant water depth and that the clinoform shape did not vary as a function of time. In subsequent analyses, process-based depositional modeling approaches using the Kenyon and Turcotte (1985) solution have, in general, violated the initial and boundary conditions. For example, Ross et al. (1994) predicted that clinoforms should steepen when prograding into deeper water. However, their prediction which builds on the Kenyon and Turcotte (1985) solution is not consistent with either the boundary or initial conditions of the diffusion differential equation.

ACCOMPLISHMENTS AND RESULTS

Our quantitative model for simulating the 3D stacking patterns of a continental margin consists of two parts: 1) an equation describing the diffusive and advective movement of sediment within the plane, and 2) a convolution in the along-margin direction. With this 3D combination of advection and diffusion along and across the margin, simulating the development of stratigraphic sequences on the margin becomes numerically straightforward. At the heart of our modeling scheme is the solution to the following differential equation (e.g., Carslaw and Jaeger, 1959):

$$\frac{\partial h}{\partial t} = k_{across} \frac{\partial^2 h}{\partial^2 x} - v_{across} \frac{\partial h}{\partial x} \qquad [1]$$

with pertinent initial and boundary conditions of:

$$\begin{aligned} h &= h_0 + ax; && x \geq 0,\ t = 0 \\ &= 0; && x < 0,\ t = 0 \\ h &= h_1 + bt; && x \leq 0,\ t > 0 \end{aligned}$$

where h is the developing seafloor topography as a function of time t, $h_0 + ax$ is the initial bathymetry (with a depositional coastal break of h_0 at $x = 0$), $h_1 + bt$ is the variation in relative sea-level, x is the spatial coordinate across the margin, k_{across} and ν_{across} are the sediment diffusivity and advection velocity across the margin, respectively. Following Carslaw and Jaeger (1959), the solution to [1] is:

$$h(x,t) = h_0 + ax - av_{across}\, t$$
$$+\ 0.5\,(h_1 - h_0) \left\{ erfc\left[\frac{x - v_{across}\, t}{2\sqrt{k_{across} t}}\right] + e^{v_{across} x / k_{across}}\, erfc\left[\frac{x + v_{across}\, t}{2\sqrt{k_{across} t}}\right] \right\}$$

$$+ \frac{1}{2v_{across}} \left(b + av_{across}\right) \left\{ (x + v_{across}\, t)\, e^{v_{across} x / k_{across}}\, erfc \left[\frac{x+v_{across}\, t}{2\sqrt{k_{across} t}} \right] \right.$$

$$\left. + (v_{across}\, t - x)\, erfc \left[\frac{x-v_{across} t}{2\sqrt{k_{across} t}} \right] \right\} \qquad [2]$$

where erfc is the complementary error function and n_{across} and k_{across} define the bulk sediment transport properties across the margin.

The advective and diffusive terms of equation [2] play an important role in controlling the geometry of the resultant clinoform. For example, for a slow increase in relative sea level and a constant sediment input rate, high advection maintains the geometry of the clinoform whereas high diffusion reduces the clinoform slope (Figures 1a & 1b). Given that diffusion minimizes bathymetric curvature while advection tends to maintain curvature implies that the long-term or steady-state condition is one that approaches a ramp morphology. We propose that margins initially characterized by a ramp configuration that eventually evolve into a margin with a pronounced shelf/slope break do so in response to a bathymetric perturbation induced by tectonics, current erosion, sediment supply, and/or inversion.

Equation [2] is particularly useful in allowing us to investigate the geometry of clinoforms developed during times of increasing water depths (Figure 1c). In this situation, we find that the clinoform dip tends to decrease as a function of time and as a function of increasing water depth. In contrast, when the rate of sediment supply is subordinate to the rate at which new accommodation is generated during a relative sea level rise, the clinoform dip tends to become steeper with time (Figure 1d). This is because the clinoforms aggrade faster than prograde and the downslope thinning within each depositional time-slice causes each successive clinoform to become steeper. Comparing Figures 1c & 1d we see that it is the difference in thickness between the bottom-set beds and the aggrading top-set beds that ultimately determines if the foreset-beds steepen or flatten with time. According to the previous models, clinoform oversteepening is a direct consequence of prograding into deeper water following a relative sea level rise. Our modeling indicates that this is an oversimplification and it would appear that there is no simple relationship between water depth and clinoform dip because the clinoform geometry also reflects the ratio between sediment supply and accommodation. In general, the modeled geometries shown in Figure 1 are characteristic of sigmoidal to oblique progradation systems indicative of regions dominated by sediment input.

SCIENTIFIC IMPACT

Geological systems are, in general, inherently 3D. Nevertheless, the present literature abounds with two dimensional (2D) modeling strategies used to simulate and extrapolate the modeled stacking patterns of basin systems. Implicit in these modeling schemes is that an understanding of the 2D is first required before dealing with 3D systems. Our initial work has clearly demonstrated that if the process is implicitly 3D, then the 2D simplification procedure will prohibit the proper understanding of the system. This is

underscored by the failure of 2D modeling schemes to predict/model a sequence boundary in response to a lowering of relative sea level. The critical philosophical step is in realizing that we must begin the problem of stacking patterns as a 3-D problem. Consequently, we now have identified the key processes we need to constrain in order to model stratigraphic sequence development.

TRANSITIONS

An important application of our research is understanding the significance of onlap surfaces. In particular, the development of an onlap surface along an evolving sedimentary basin is a consequence of along-axis sediment transport. This has critical implications for the porosity and permeability structure of the facies within onlapping stratigraphic sequences and therefore the associated acoustic properties.

RELATED PROJECTS

The goals of this project interface with and complement the objectives of a number of ongoing and proposed research projects within the ONR STRATAFORM Initiative.

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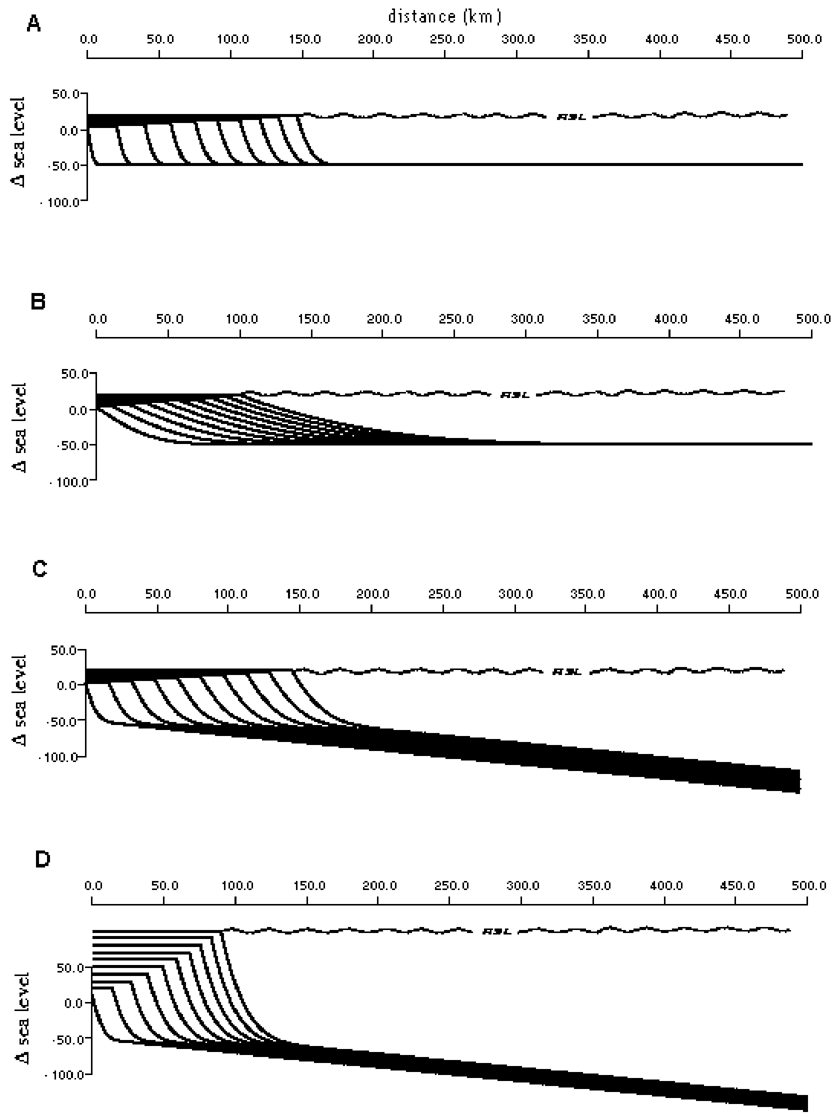

Figure 1. Various modeled clinoform geometries using equation [2] illustrating the effect of high advection **(A)** and rapid diffusion **(B)**. Advection serves to maintain the shape of the clinoform, diffusion attempts to minimize curvature of the clinoform. **(C)**. The effect of increasing water depth on clinoform geometry by changing the depositional slope. In this example, the sediments are allowed to prograde into a ramp setting with an offset of -50 m at x = 0. Relative sea level was rising during deposition and the clinoform dip decreases as a function of time. **(D)**. When the increase in accommodation is much greater than the rate of sediment supply, it causes the clinoform to become more aggradational than progradational. Thus, the clinoform dip increases.